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Economic growth and technological change: A comparison of insights from a neo-classical and an evolutionary perspective

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Abstract

Over the last two decades, dissatisfaction with the traditional Solow-Swan model of economic growth resulted in two new classes of models of economic growth and technological change: neo-classical endogenous growth models, and evolutionary growth models. The first class of models has been labeled endogenous, because of its key feature of endogenizing technological change. The second class of models endogenizes technological change as well, but according to an evolutionary view on economic growth and technological change. In this paper we discuss the insights from both the neo-classical and the evolutionary perspectives. It is argued that in evolutionary models technological and behavioral diversity, uncertainty, path dependency, and irreversibility are elaborated in a more sophisticated and explicit way than in neo-classical growth models. However, this level of microeconomic diversity comes at a certain price. Due to the complexity of the models, which preclude analytical tractability, the mechanisms behind the aggregate dynamics are not always clearly exposed. In addition, it will be argued that the neo-classical and the evolutionary approach are converging in the Schumpeterian framework. The latter framework is developed in both classes of models as a means for theorizing on technological change. A challenging task for further research is to combine the fruitful insights of both the neo-classical and the evolutionary approach to improve our understanding of complex processes of technological change in relation to other micro- and macroeconomic processes. © 2001 Elsevier Science Inc. All rights reserved.

Keywords: Evolutionary growth theory; Neo-classical growth theory; Technological change

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1. Introduction

The traditional, neo-classical model of economic growth was first developed by Solow [1] and Swan [2] in the 1950s. In the 1980s, during an economic slowdown, that model was criticized as it explained economic growth, and more specifically technological progress, by simply postulating it. It is, therefore, not surprising that alternatives for the traditional framework were developed in the early 1980s (see, e.g., [3]). The two major alternatives to the traditional neo-classical growth model are the neo-classical endogenous growth models as pioneered by Romer [4] and Lucas [5], and the evolutionary models, of which the foundations have been laid down in the seminal work of Nelson and Winter [6]. Both classes of models are less homogeneous than the “old” neo-classical model of economic growth. They both strive for a better understanding and a more realistic depiction of the complex process of technological progress. The two classes of models differ with respect to their acceptance of tools and insights from neo-classical economics and their opinion about the extent to which the real world can be described as developing along a smooth path.

In this paper we discuss the insights and views from both the neo-classical perspective and the evolutionary perspective on technological change. Furthermore, we compare both perspectives so as to identify essential differences as well as similarities. These will be discussed along three central issues in the debate on technological progress: the importance of, respectively, heterogeneity, uncertainty, and path dependency. The organization of this paper is as follows. We first provide an overview of neo-classical models of economic growth and technological change. Both “old” (exogenous) growth models and “new” (endogenous) growth models are discussed. Next, we present the evolutionary perspective. Subsequently, the two approaches will be compared. A final section concludes.

2. Growth theory: a neo-classical perspective

This section presents a short overview of economic growth theory from a neo-classical perspective. Rather than providing a detailed survey, the aim of this section is to provide the key characteristics of the different models as well as a brief discussion of the mechanisms that drive growth in both exogenous and endogenous growth models. For more complete surveys of neo-classical growth models we refer to, among others [5,7–11].

2.1. *Exogenous growth theory*

When thinking about economic growth, a natural starting point is the Solow-Swan growth model [1,2]. This model can be seen as the benchmark for what is now called the neo-classical theory of growth. The Solow-Swan model aims to provide a theoretical framework for understanding world-wide growth of output and the (persistence of) geographical differences in per capita output. Aggregate output (Y) depends on capital (K) and labor (L) according to a constant returns to scale production function. Technological progress is introduced in terms of an aggregate parameter (A) reflecting the current state of labor-

augmenting technological knowledge. Taking a Cobb-Douglas production function, which is consistent with the stylized fact of constant labor- and capital-income shares, we arrive at:

$$Y = (AL)^{1-\alpha} K^\alpha, \quad 0 < \alpha < 1. \quad (1)$$

The model assumes constant returns to capital (K) and effective labor input (AL), and perfect competition. The productivity parameter A is supposed to grow at an exogenously determined constant rate g . The growth rate of the labor force (n), as well as the saving rate (s), are assumed to be constant and exogenous. This latter assumption of an exogenous savings rate is not central to the neo-classical model of growth, but simplifies the analysis at this stage; we return to this assumption below. On the basis of these assumptions, an economy, regardless of its starting point, converges to a balanced growth path where long-run growth of output and capital are determined solely by the rate of labor-augmenting technological progress and the rate of population growth. A crucial property of the above production function is that there are diminishing returns to the accumulation of capital at the economy-wide level. The rate of change of the stock of capital per capita (in efficiency units), $k (= K/AL)$, depends positively on the savings rate, and negatively on the rate of population growth, the rate of technological progress, and the depreciation rate (δ), according to:

$$\dot{k} = sk^\alpha - (n + g + \delta)k. \quad (2)$$

A steady state is defined by the situation in which output and capital grow at the same proportional rate as the effective population (AL), resulting in a constant capital intensity (k). This implies that output and capital per capita will grow at the exogenous rate of technological progress (g). In other words, the economy converges to a steady state in which diminishing returns are exactly offset by exogenous technological progress. Modifying the model by allowing for intertemporally optimizing behavior of consumers resulting in an endogenous savings rate (cf. Cass-Koopmans-Ramsey) does not alter this basic conclusion (see, e.g., [4,12]).

As already mentioned, both technological progress and population growth are assumed to be exogenous in the Solow-Swan model. Obviously, here we touch upon the main shortcoming of the “old” neo-classical approach: it takes as given the behavior of the variables that are identified as the driving forces of growth. That is, it explains growth by simply postulating its existence. Furthermore, although the Solow-Swan model fits some stylized facts (cf. [13]),¹ when used for growth accounting it turns out that the model is unable to explain growth rates of output by relying on the accumulation of physical inputs (capital and labor); once output growth is corrected for the increase in physical inputs, a large and persistently positive residual remains, the so-called Solow-residual (see, e.g., [14–16] for recent applications of growth-accounting). Therefore, factors other than capital accumulation and an increasing labor force should be held responsible for most of the economic growth that has occurred. The Solow residual is often referred to as

¹ These facts are that (i) the growth rates of labor, capital, and output are each roughly constant; (ii) the growth rates of capital and output are roughly equal; (iii) the growth rates of capital and output are higher than the growth rate of labor, implying that output per worker and capital per worker are increasing over time.

the “measure of our ignorance.” It captures the fundamental driving force behind economic growth, namely technological progress. The endogenous growth theory to which we turn next, aims at contributing to our understanding of the driving forces behind technological progress.

2.2. *Endogenous growth theory*

Endogenous growth theory encompasses a class of models that goes beyond Solow-Swan by endogenizing technological change. One of the first attempts to endogenize technology was made by Arrow [17], who assumed that the growth rate of the effectiveness of labor is a result of workers’ cumulated experience in producing commodities, or in other words, the result of “learning by doing.” This implies that the labor productivity is now endogenous, being an increasing function of cumulated aggregate investment by firms. An important characteristic of the Arrow model is that learning is conceived as a public good; it is the result of experience at the level of the whole economy, and can be applied by all firms at no cost. This also means that in deciding how much to invest, firms ignore the effect of their investment on the total amount of knowledge in the economy because the effects are external to each individual firm.

A major step forward in endogenizing technological progress was set by Romer [4], who builds upon the contributions of Frankel [18] and Arrow [17]. The basic idea of his approach is that technology grows in proportion to the macroeconomic capital stock, potentially offsetting the effects of diminishing returns. Capital in such a setting should be considered as a broad concept, including human and intangible capital. This approach is currently known as the “AK approach” because it results in a production function of the form $Y = AK$ with A constant. The individual firm’s production function reads:

$$Y_i = [A_i(K, L)L_i]^{1-\alpha} K_i^\alpha. \quad (3)$$

Crucial in this formulation is that the index of knowledge available to the firm is linked to the economy wide stock of capital and labor. This is based on the idea that each firm’s knowledge is a public good that any other firm can access at zero costs. Accordingly, the change in each firm’s technology term A_i is related to the change in the aggregate capital and labor stock, which the individual firm cannot influence (they are external to the firm). A simplifying specification for A_i that is often used is:²

$$A_i = [AK^\beta]^{1/(1-\alpha)}, \quad (4)$$

² A more general specification would be

$$A_i = [AK^\beta L^{-\phi}]^{1/(1-\alpha)}.$$

We then arrive at $Y = AK^{\alpha+\beta} L^{1-\alpha-\phi}$. So, again, long-run growth can be sustained with constant population provided that $\alpha + \beta \geq 1$.

in which the change in technology only depends on the rate of macroeconomic capital accumulation. Aggregating over all firms, we arrive at the aggregate production function:

$$Y = AK^{\alpha+\beta}L^{1-\alpha}. \quad (5)$$

In the special case in which $\alpha + \beta = 1$ and L is normalized at 1, the production function boils down to $Y = AK$. Long-run economic growth can be sustained in the long run without relying on exogenous technological progress.³ The rationale for this approach in which technological development or learning is external to the firm, lies in the difficulty of dealing with increasing returns in a general equilibrium framework. By introducing a (Marshallian) externality, a competitive equilibrium, in which capital and labor receive their marginal products can exist. In other words, there exist constant returns to scale at the firm level and increasing returns at the economy level due to increasing knowledge.

In conclusion, the essential idea of the Romer [4] model is that knowledge can be considered as a kind of renewable capital good, where K should be interpreted as knowledge. Within the model, long-run growth is determined by the (still unintended) accumulation of knowledge through representative individuals who maximize intertemporal utility (Ramsey model). The crucial assumption in this Romer model is that knowledge does have a nondecreasing marginal product, that is $\alpha + \beta \geq 1$. This can be interpreted as allowing for nondecreasing social returns to capital (knowledge) resulting in nondecelerating growth. In contrast with the Solow-Swan model of growth, a positive growth rate of output can be sustained without population growth and exogenous growth of technological progress.

It should be noted that this class of models has a knife-edge character due to the assumption of constant returns to scale with respect to reproducible factors. Any deviation from this assumption will have significant effects in the (very) long run. With slightly decreasing returns growth will vanish in the (very) long run, whereas with slightly increasing returns growth will accelerate indefinitely (as in Romer [4]). As a consequence, the explanatory power of endogenous growth models with respect to changing technology variables for the very long run cannot be taken too literally. One cannot preclude that reality is characterized by slightly increasing or decreasing returns to scale.⁴ Nevertheless, it can be argued that this weakness is of relatively minor importance, because with sufficiently large elasticities of reproducible factors (which seem to be the empirically relevant case), transition periods in which technology variables change are very long (see also [20] for a discussion of

³ The analyses of Romer [4] and Arrow [17] essentially differ in that Arrow still assumed diminishing marginal productivity of capital at an economy wide level for a given supply of labor. Because in such a case increasing knowledge cannot fully compensate for the diminishing returns to the firm's stock of capital, long-run growth will cease unless the (exogenous) rate of growth of the labor force (population growth) is sufficiently high. Therefore, long-run economic growth still depends on an exogenous factor. Nevertheless, the model of Arrow can be referred to as an endogenous growth model *avant la lettre*. It is also to be noted that the AK approach in endogenous growth theory is essentially a straightforward extension of the Harrod-Domar model, "but with sophisticated bells and whistles" ([19], p. 49).

⁴ Hence, the crucial question here is: "how long is the long run?" To state the problem in the words of Solow: "It is one thing to say that a quantity will eventually exceed any bound. It is quite another to say that it will exceed any stated bound before Christmas" ([19], p. 50).

the speed of transition in the context of the neo-classical model of growth). This implies that endogenous growth models, despite their knife-edge character, yield useful insights into the process of endogenous technological change for long periods of time, although not indefinitely. We refer here also to [21] for a recent convincing theoretical and empirical defense of the *AK* growth models.

As a way of summarizing, Fig. 1a and 1b present the steady state outcomes of, respectively, exogenous and endogenous models of economic growth with Ramsey consumer behavior.

The figures basically depict equilibrium on the capital market, where funds are supplied by consumers who save part of their income with the aim of smoothing their consumption profile over time. Funds are demanded by producers who need money for investment in growth-promoting activities. The supply of funds by consumers satisfies the Ramsey rule, according to which there is a positive relationship between the growth and the interest rate. The positive slope is due to the fact that consumers who wish to smooth their consumption profile are only willing to accept a high growth rate (that is, a steep consumption profile), provided that they are compensated by a high interest rate. This relationship holds independent of whether we have an exogenous or an endogenous growth model. Assuming a constant pure rate of time preference (θ) and coefficient of risk aversion (ϕ), one arrives at the Ramsey formula $g = (r - \theta)/\phi$. On the demand side of the capital market are the producers who need funds to finance their investments. In the neo-classical (exogenous) growth model, the demand for funds is represented by a vertical line at the growth rate equal to the exogenous rate of technological progress (g). This demand for funds is independent of the interest rate r (Fig. 1a). The intersection of this line with the line representing the Ramsey rule yields the solution for the steady state interest rate (i.e., the steady-state marginal product of capital). In the basic *AK* approach as set out above, the long-run growth rate of capital and output are determined endogenously, whereby the demand for funds satisfies the condition that the marginal product of capital equals A (that is, the relationship between the growth and the interest rate is horizontal in Fig. 1b). Again, the equilibrium growth rate is found at the intersection of this line with the line representing the Ramsey rule (Fig. 1b).

Although the presence of externalities and nondiminishing returns to scale in the final goods sector is an important characteristic of the basic *AK* model of endogenous growth, subsequent developments have generalized the basic model in several ways. Rebelo [22] demonstrated the feasibility of sustained endogenous growth without the need for constant returns to scale with respect to reproducible factors in the final goods sector and without the presence of externalities. The underlying idea is that all that is necessary is a “core” of reproducible capital goods or knowledge entering into final goods production (with potentially diminishing returns) that is produced in some sector of the economy without the direct or indirect contribution of nonreproducible factors and with (at least) constant returns to scale.

Yet another route that has been taken in the development of endogenous growth models is the modeling of growth as resulting from intentional microeconomic activities aimed at profit maximization in the context of imperfectly competitive general equilibrium models. These models no longer rely on pure externalities resulting (unintentionally) in nondiminishing

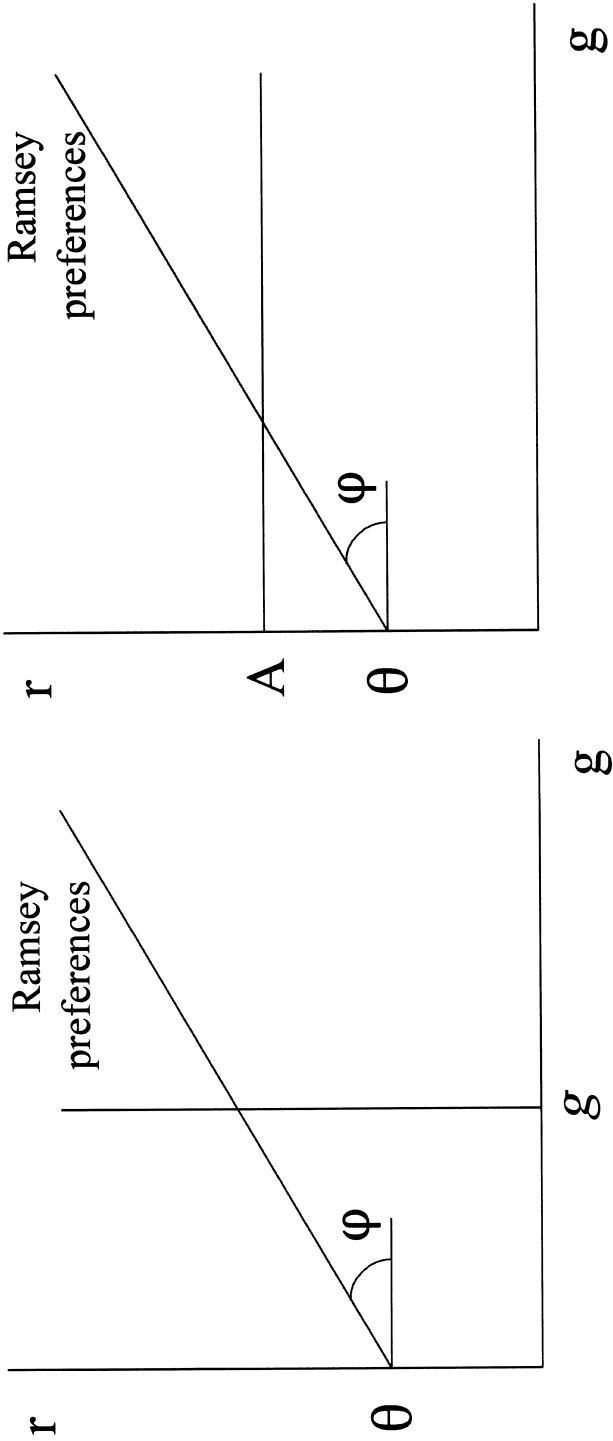


Fig. 1. (a) Neo-classical model of exogenous growth; (b) basic AK model of endogenous growth.

returns with respect to accumulative factors at a macro-economic level (e.g., [5,23]). An important issue in these models is the extent to which the returns to investment are appropriative and the extent to which they spill over to other agents in the economy.

A third route that has been explored is the development of multi-sector models. These models are obviously not only more realistic, but they are also of importance when nonreproducible inputs are essential in the production process. Technological progress is then needed to counterbalance the tendency of ceasing long-run growth through decreasing returns to those factor inputs. The usual way to model intentional technological progress is to make a distinction between a research sector and other sectors. The allocation of resources between the R&D sector and the other sectors is determined by relative returns (e.g., [24]).

The important characteristic of all models of endogenous growth is that the rate of growth can, in contrast with the traditional neo-classical model, be influenced by economic policies (even in the long run). Many of the models also require government intervention from a socially optimal point of view due to the existence of externalities like knowledge spill-overs (intertemporal as well as between firms at one point in time) that are characteristic for many endogenous growth models.

The most recent development in endogenous growth theory is the so-called neo-Schumpeterian approach to endogenous growth theory. The essential characteristic of this approach is the existence of “creative destruction,” that is, the occurrence of a succession of innovations in one or more sectors, resulting from research activities, and implying a business stealing effect. An example of a Schumpeterian model of endogenous growth is in [25], where growth is fuelled by a random sequence of quality improving innovations. The innovations “arrive” according to a stochastic Poisson process, and result from (uncertain) research activities. One of the implications of this model is again that the laissez-faire growth rate may be different from the socially optimal growth rate. The reason for this is the existence of three counteracting effects: the business stealing effect, the intertemporal spillover effect, and the appropriability effect. The latter refers to the private monopolist’s inability to appropriate the whole output flow. Both the appropriability effect and the intertemporal spillover effect tend to generate insufficient research under laissez-faire in terms of what is socially optimal because private research “firms” do not internalize positive social externalities. The business-stealing effect, on the other hand, tends to generate too much research under laissez-faire in terms of what is socially optimal, because it ignores the costs of obsolescence of old intermediate inputs. In case the business-stealing effect dominates, laissez-faire growth will be excessive. Again, this implies a rationale for government intervention.

3. Growth theory: an evolutionary perspective

Dissatisfaction with the Solow-Swan model of economic growth (see above) has not only led to the wave of “new” neo-classical or endogenous growth models as described in the previous section, but also to evolutionary theorizing on economic growth. The benchmark study here is the classic book of Nelson and Winter [6], which exposes an

evolutionary view on economic growth and technological change. The work of Nelson and Winter can be seen as an “evolutionary response” to the shortcomings of the “old” neo-classical theory of economic growth. The development of evolutionary growth models resulted in a revival of the evolutionary tradition in economics, which goes back to Veblen [26] and Schumpeter [27]. The idea that technological change is a fundamental driving force of economic development is at the heart of evolutionary theorizing about economics in general and economic growth in particular. Of course, the crucial role of technological progress in bringing about economic growth has been recognized in neo-classical economics as well. However, what distinguishes evolutionary from neo-classical economics is its theoretical framework.

The differences between the two theoretical frameworks arise essentially from the objections evolutionary economists have to the (aggregate) production function as it is used by neo-classical economists. The neo-classical production function can be defined as a specification of all conceivable modes of production in light of the existing technological knowledge about input–output relationships [28]. It is common practice among neo-classical economists to distinguish between a movement along the production function, referring to factor-input substitution, and a shift of the production function, referring to technical progress. Among others, Nelson and Winter [6,29,30], Dosi [31], and Sahal [28] have argued that this view on production and technological progress suffers from providing no insight in the occurrence of technical innovation processes, because the development of new techniques (“blueprints”) is exogenous to the economic process (a criticism that does not apply to the class of endogenous growth models). Furthermore, evolutionary economists argue that the neo-classical production function does not comply with what empirical research tells us about the nature of technological change and the characteristics of innovative firms.

Following Dosi [32], the major findings of the (microeconomic) literature on sources, procedures, directions, and effects of technological change can be summarized as follows:

1. Innovative efforts are characterized by varying degrees of appropriability and uncertainty about the technical and commercial outcomes.
2. Technology embodies a certain degree of tacit knowledge that is firm specific, local, and cumulative (“expertise”).
3. Innovations result from search and learning processes of individuals or organizations (firms). Knowledge-building and problem-solving activities are characterized by organizational or behavioral routines (“bounded rationality”; “satisficing”).
4. As a result of 1 and 2, technologies develop along relatively ordered paths (“trajectories”) within the boundaries of firms or technological paradigms. The latter refers to a collective framework that determines the R&D practice and the pattern of technological development on the basis of a dominant design of an artefact. Technologies may well get locked-in to paradigms, implying a certain degree of irreversibility (“history matters”).
5. As a result of 1, 2, 3, and 4, the diversity of techniques used within and between firms and sectors is a fundamental characteristic of an economy undergoing technological change.

On the basis of these findings, a whole body of literature has been developed within evolutionary economics, addressing the “evolution of the production function.” In the literature, the occurrence of technical innovation is made endogenous according to an evolutionary line of reasoning. An in-depth discussion of the literature embodying evolutionary theorizing on technical change is beyond the scope of this paper. For lucid surveys we refer to [33–37].

With respect to evolutionary theorizing on economic growth, the basic formalization draws on what are now called “replicator equations” [38]. In biology, these equations were introduced by Fisher [39], and can be seen as a formalization of Spencer’s notion of the survival of the fittest.⁵ Replicator equations describe the evolution of a population according to:

$$x_i = x_i(f_i(x) - \bar{f}(x)), \quad i = 1, \dots, n \text{ with } \bar{f}(x) = \sum_{i=1}^n x_i f_i(x), \quad (6)$$

where x is the vector of relative frequencies of the species (x_1, \dots, x_n) , n reflects the number of distinct competing “species” of a population, and $f_i(x)$ reflects the frequency-dependent fitness of species i . This implies that species with above-average fitness will expand in relative importance, those with below-average fitness will decrease, while the average fitness $\bar{f}(x)$ changes with the relative population weights. Assuming constant fitness functions, it can be shown that the species with the highest fitness will displace all the others, and that average fitness is dynamically maximized by the evolutionary process.⁶ When fitness functions change endogenously, the replicator equation describes relative share dynamics. In evolutionary economic models, f_i is generally defined in terms of market competition or differential profit rates, thereby functioning as the selection mechanism. The entities (i), on which selection takes place, are “translated” to firms, techniques, or products [41], while the share of competing “species” of a population level x_i usually refers to the market shares.

As a result, evolutionary economic models are characterized by an explicit microfoundation, allowing for heterogeneity. This is an important characteristic that also holds for evolutionary growth models. In the Nelson and Winter growth model [6], heterogeneity is defined in terms of firms: different firms possess different capabilities, procedures, and decision rules that determine their action. Firms use production techniques (characterized by fixed labor and capital coefficients) to produce a homogeneous output. Novelty, here defined as process innovation, is a result of search activities of individual firms with “search” denoting a firm’s R&D activities. The search process (“mutation”) may consist of imitation or local search. In the first case, firms explore techniques already used by other firms. In the second case, firms search for new techniques in a (given and finite) pool of existing but yet undiscovered techniques. The search process is guided by satisficing behavior (cf. [42]): firms only undertake a search process if their rate of return on their employed techniques falls

⁵ It was Spencer, not Darwin, who coined the phrase “survival of the fittest” (see [40]).

⁶ This is known as Fishers Fundamental Theorem of Natural Selection.

below an (arbitrarily determined) value. The rate of return on techniques drives the selection process in the following way. Assuming that techniques differ only with respect to their labor productivity, and that firms reinvest their profits in capacity expansion, the more productive and profitable technique gradually replaces the less productive one, depending on the form of the wage function.

The Nelson and Winter model is analyzed by means of simulation because of the complexity arising from the simultaneous existence of multiple firms with different search behavior, and hence, different technological levels. Nelson and Winter show that their model is capable of generating the patterns of aggregate output (GNP), capital input, labor input and factor prices, as addressed by Solow [43] in his pioneering contribution to growth theory. Although the empirical validation of the Nelson and Winter model is highly specific to Solow's data set, Nelson and Winter have argued on the basis of this outcome that an evolutionary model is preferable over a neo-classical one because it may explain macro-economic facts about productivity growth, "through the route of 'building them up' from microeconomic data" ([6], p. 209). It is mainly this argument that has given the Nelson and Winter model its paradigmatic function of being the starting point for a revival of evolutionary economic theorizing.

A number of evolutionary growth models has been developed that is inspired by the Nelson and Winter model. The most important common factor in these models is the modeling of a selection process, on the basis of replicator equations, as the driving force of economic growth. The selection process continually modifies the technological variety, which may be embodied in firms, sectors or countries.

Conlisk [44] has developed a simple aggregate growth model in which technological change is endogenous and "cumulative." The latter refers to the Nelson and Winter model and the replicator dynamics in the following way. Technological change is defined in terms of the productivity of firms. The economy constructs new firms with productivities that distribute around the mean of a (normal) probability distribution. A new firm with a (labor) productivity that is sufficiently higher than the average productivity is viewed as an innovation that improves standards for future firms. This implies that technological change increases the mean of the productivity distribution.⁷ Because the new firm's technology is assumed to build on the innovative firms of the past, rather than on the average firms of the past, innovation causes productivity to grow at the economy level. The growth rate of the economy is a function of the savings rate, the speed of diffusion of new knowledge, and the standard error of the productivity distribution of new firms. The latter can be interpreted as the average innovation size. Due to a number of simplifications, this model is one of the very few evolutionary growth models that yields analytical solutions.

⁷ It is to be noted that, despite its unconventional ("evolutionary") form, the model of Conlisk [44] can accommodate standard patterns of the neo-classical literature on economic growth. Conlisk demonstrates that, because technological change is modeled through shifts in the mean of the productivity distribution, respecification of the productivity measure (i.e., the mean of the productivity distribution) enables his model to reproduce exogenous technical change as in Harrod-Domar and Solow-Swan [1,2], learning by doing as in Arrow [17], and incremental learning by doing as in Romer [4].

In Silverberg and Lehnert [45,46], technological variety arises according to a time-homogeneous or inhomogeneous Poisson distribution. Again, the replicator mechanism is driven by profit rates. As in the Nelson and Winter model, techniques with different labor productivity yield different profit rates, and profits are subsequently reinvested in those same techniques. Hence, techniques with above-average productivity will expand, new techniques diffuse into the economy due to their superior profitability, and techniques with below-average productivity (and, hence, profitability) will contract. This led the authors to label their model “Schumpeterian,” referring to Schumpeter’s notion of creative destruction. More specifically, the stock of capital (k) embodied in a qualitatively distinct technology (i) evolves according to:

$$\frac{k_i}{k_i} = r_i + s(r_i - \bar{r}) - \gamma = \frac{1}{c_i} \left(1 - \frac{w}{a_i} \right) + s(r_i - \bar{r}) - \gamma, \quad (7)$$

where r_i is the rate of profit of technology i , \bar{r} is the capital stock weighted average profit rate, s a constant representing the strength of the crosstechnology investment, γ is the depreciation rate of physical capital, c_i is the capital output ratio, a_i is the labor productivity, and w is the real wage. Essentially, the model is a multitechnique version of Goodwin’s growth cycle model [47], and therefore, mathematically equivalent to a multidimensional Lotka-Volterra system with stochastically perturbed coefficients.⁸ In other words, the mathematical method on predator–prey relationships is used to derive the selection process. Let f_i be the share of technology i in total capital stock, where technologies with above-average profit rates grow in share according to:

$$f_i = (1 + s)(r_i - \bar{r}). \quad (8)$$

As a result, long-run fluctuations in productivity growth are produced within the model, basically driven by innovations. In this context, a reference is made to earlier work of Schumpeter and Kondratieff on the relationship between innovation, diffusion, and macroeconomic dynamics.⁹

In the growth model of Verspagen [48], heterogeneity is defined in terms of sectors. Sectors differ with respect to the produced goods and labor productivity. Again, the latter is an indicator for the technology used. A replicator equation in which sectors compete with each other on the basis of production costs (consisting of technological, labor, and exchange rate costs) is responsible for the selection process. This multisectoral model highlights the interaction between specialization and growth by making technological performances of countries dependent on their specialization pattern. Simulation outcomes show that differences between technological potentials of sectors and countries may give rise to persistent differences in growth rates.

⁸ The system of Lotka-Volterra equations describes predator–prey interactions based on growth equations for the interacting population levels. They can be interpreted as an alternative description of basically the same dynamics described by replicator equations.

⁹ Edenhofer and Jaeger [54] have recently applied this approach in the field of energy technologies.

Following the Nelson and Winter approach, a number of models has been developed that takes an explicit microeconomic foundation, i.e., in the meaning of modeling individual firm behavior (e.g., [49–52]). In these models, differences between firms arise not only from technological differences (in terms of input coefficients), but also from economic strategies followed by firms. The latter refer to price setting of products (based on demand expectations) or decisions about the investment of resources in the search for new techniques. In general, the probability of innovation depends on R&D efforts. These models differ from one another with respect to, among others, the fact of whether or not firms possess skill levels that evolve by a learning process, R&D strategies that can change over time, and R&D or technological spillovers that play a role.

4. Neo-classical versus evolutionary perspectives on economic growth: searching for the essential differences

As noted above, recent evolutionary theorizing on economic growth and technical change evolved out of dissatisfaction with the (empirical) performance of the traditional neo-classical approach to economic growth. In the words of Nelson and Winter: “The weakness of the (neo-classical) theoretical structure is that it provides a grossly inadequate vehicle for analysing technical change. In particular, the orthodox formulation offers no possibility of reconciling analyses of growth undertaken at the level of the economy or the sector with what is known about the processes of technical change at the microlevel” ([6], p. 206). Obviously, part of the criticism on neo-classical models of economic growth has been superseded by the development of the endogenous growth theories that are in accordance with the neo-classical framework. Still, from an evolutionary point of view, a number of objections or critics to the new neo-classical or endogenous growth theories persists [53]. Essentially, these can broadly be summarized in two points: (1) a large gap still exists between the stylized and formal treatment of technologies in the endogenous growth models based on rational and optimizing behavior and what is known from microeconomic studies on technology and technological change, firm behavior, and institutions. In other words, new neo-classical growth theory still contains too much a “stylised, stripped down, inadequate view” ([53], p. 319); (2) The new neo-classical growth models continue to treat economic growth as a smooth process involving a continuous tendency to return to an equilibrium state.

In this section we explore the differences between the evolutionary and the neo-classical approach to economic growth and technological development. The aim of this section is to investigate to what extent the differences are essential in terms of modeling. We have chosen to discuss the differences between the two approaches along a classification of issues that are central in the debate on technological progress, namely the view on technology, heterogeneity, uncertainty, and path dependency. By taking into account these issues explicitly, evolutionary economics claims to distinguish itself from neo-classical economics [6]. For this reason we will investigate in particular the value added of evolutionary growth models in terms of their outcomes on the basis of these issues.

4.1. Technology

In the Solow-Swan model technology is incorporated as an exogenous factor representing knowledge as a nonrival or public good. In the initial attempts to endogenize technology in neo-classical growth models, several definitions of knowledge have been used. In the Arrow model, knowledge creation is defined as “learning by doing.” Although still a public good for individual agents, knowledge is supposed to increase as an (unintended) side effect of production activities at the economy level. In other neo-classical contributions, knowledge is interpreted as scientific knowledge, characterized by lack of both private returns and property rights [55–58]. It is this view on technology that has been heavily criticized by evolutionary economists.

As we tried to stress previously, an essential characteristic of the wave of endogenous growth models is a broadening of the capital definition. This is mainly done by defining capital not only in terms of physical capital, but also in terms of human capital. Knowledge accumulation, in one way or the other, is at the heart of all models on endogenous economic growth, because it is responsible for sustained endogenous growth. For example, in [4], [5], [15], and [22], knowledge is defined as the factor responsible for increasing the capital productivity, with capital broadly defined encompassing both physical and human capital.

Although the early approaches in endogenous growth theory modeled technological progress as a side effect of economic activities, recent endogenous growth models explicitly take into account intentional technological progress. For example, in [24], [59], [60], and [61], knowledge results from intentional R&D activities. The return on investment in research activities consists of monopoly rents generated by (blueprints of) new intermediate inputs that result from R&D activities. Allowance is made for innovative efforts that are characterized by varying degrees of appropriability and technology that may have a certain degree of tacitness [61,62]. In the Schumpeterian approach [7,25] to endogenous growth theory—which we call the “neo-classical Schumpeterian approach”—a more vertical way of modeling technological progress is employed, taking into account the obsolescence of old intermediate outputs as an integral component of technological progress. Allowance is also made for uncertainty in the arrival of new technological opportunities.

Following Nelson and Winter [6], evolutionary growth models also embody a Schumpeterian perspective on economic growth and technological progress. Therefore, they will be called the “evolutionary Schumpeterian” type of models hereafter. Whereas the “neo-classical Schumpeterian” type of model is still an equilibrium model including typical neo-classical decision-making principles like profit maximization and rational expectations, the “evolutionary Schumpeterian” type of models drop these features. Further differences between the “new” neo-classical and evolutionary models of growth fuelled by innovation and “creative destruction” can be traced back to the way in which heterogeneity, uncertainty and path dependency are considered. In evolutionary growth models these issues are presented as crucial components of economic growth and technological progress. Evidently, this results in a more diverse and complex representation of the Schumpeterian view than in neo-classical endogenous growth models (see, e.g., [49,63]). Below we will investigate to what extent the evolutionary contribution to growth theory has gained

additional insights by elaborating on these issues. Still, it is fair to conclude that over the last few years, the views on technology expressed by evolutionary and neo-classical economists have converged.

4.2. Heterogeneity

The modeling of technological and behavioral differences between technologies, sectors, or countries, can be considered as an important feature of evolutionary growth models. By modeling this heterogeneity, evolutionary economics claims to provide a more sophisticated microeconomic foundation for explaining macroeconomic patterns. In general, microeconomic diversity is defined in terms of technological differences that influence macroeconomic patterns by means of the selection process, as described previously.

In Conlisk's model [44], heterogeneity plays a crucial role. Heterogeneity is defined at the level of firms that differ with respect to their technological features, measured in terms of labor productivity. As described before, innovations increase the average productivity of the firms, which is modeled as the mean of the probability distribution reflecting the productivities of the firms. The specification of this mean is critical to the outcomes of the model.

A more sophisticated representation of heterogeneity can be found in the models that take into account behavioral differences among firms. For example, Chiaromonte and Dosi [49] model a complex disequilibrium process of innovation, imitation, and competition, where the aggregate patterns of productivity and growth are interpreted as the outcome of an evolutionary or self-organizational process driven by endogenous learning and market selection. In this model, as well as in [50], [51], and [52], behavioral and technological diversity among agents is a crucial ingredient of the system dynamics. The behavioral diversity is modeled by assigning fixed decision rules to agents, which are different in their decision parameters. These decision rules attempt to reflect what is known from the literature on innovation processes, as we have summarized in the previous section. In [49], the most concrete effect of modeling heterogeneity among the agents on aggregate dynamics is the instability of the relationship between productivity growth and income growth that appears from simulations. By way of explanation, it is suggested that variations in appropriability, above a certain minimum threshold, have ambiguous effects on growth. Although the model simulation shows that appropriability is a necessary condition for innovation because it is obviously beneficial to individual innovators, appropriability may also slow down technological diffusion, and thereby aggregate growth in productivity and income.

In Verspagen's model [48], heterogeneity is defined in terms of sectors that differ with regard to the produced product and labor productivity (technology). At the aggregate level, selection is a function of sectoral shares in total consumption, which evolve according to different real-income elasticities in different countries. In [49], two related sectors are modeled. One sector produces heterogeneous production inputs ("machines") with labor, the other sector produces a homogeneous consumption good with labor and "machines." In both models sectoral heterogeneity enables an interaction between the supply and demand side of the economy. Innovation and diffusion processes in the sector

that produces input goods are driven by the demand of the other sector, which produces consumption goods.

It is to be noted that the “neo-classical Schumpeterian” literature also addresses the ambiguous relation between appropriability and productivity growth. In [7] (chapter 7), the issue is discussed in terms of the relationship between competition and growth. A distinction is made between competition in the product market and in the innovation sector. The analysis shows that competition in the innovation sector is likely to correlate positively with growth, whereas product market competition features an ambiguous relationship with productivity growth. It is suggested that for a better understanding of the trade-off between the positive and negative appropriability effect, it is necessary to classify the economy in subgroups. In short, both approaches to Schumpeterian dynamics stress the importance of heterogeneity, but so far this feature has only been elaborated upon in “evolutionary Schumpeterian” growth models.

In summary, it appears that evolutionary growth models deal with technological and behavioral diversity in a more sophisticated and explicit way than neo-classical growth models. In the latter class of models, the emphasis is on one- or two-sector economies with representative agents and commodities. The simultaneous consideration of firms or sectors with different technological characteristics gives the evolutionary approach its value added here. However, it has to be noted that this level of microeconomic diversity comes at a certain price. Due to the complexity of the models, which precludes analytical tractability, the mechanisms behind the aggregate dynamics are not always clearly exposed (see, e.g., [49]).

4.3. Uncertainty

Evolutionary growth models are nondeterministic models, representing the uncertainty inherent to evolution in general and to innovation (diffusion) processes in particular. Usually, the models include a certain degree of uncertainty by representing the innovation process as a stochastic process. In the Nelson and Winter model [6], the probability of techniques to be discovered is represented as a Markov process. In [42], where innovation is defined in terms of newly entering firms, innovations are generated as random drawings from a normal probability distribution. Motivated by an empirical literature review, Silverberg and Lehnert [45,46] have used three stochastic processes to model the occurrence of innovations. They model a homogeneous and a logistically Poisson process as well as an innovation arrival rate that depends on economic variables (lagged profits). Chiaromonte and Dosi [49] model innovation as a two-stage stochastic process. The first stage refers to the access to the creation of a new technological paradigm (a set of technological typologies). The second stage refers to the addition of a new typology to the set, once access to the paradigm has been established. In addition, actual access to a machine and imitation of machines of other firms occur in similar two-stage stochastic processes.

In short, uncertainty is at the heart of the “evolutionary Schumpeterian” growth models because technological progress is essentially modeled as a stochastic process. However, it is

to be noted that uncertainty may also play a role in a mainly deterministic setting. This has been shown, for example, in recent neo-classical theory where attention has been paid to the Schumpeterian notion of “creative destruction” (see [25]), and to investment under uncertainty and irreversibility (see [64]). The former captures innovation as a stochastic process resulting from uncertain research activities. In the theory of investment under uncertainty and irreversibility, uncertainty is included as a condition under which deterministic decision making takes place. The essential idea is that in the case of irreversible investments, it may be rational not to invest immediately in technologies with an expected positive net present value, but to postpone the investment until new information becomes available. Because additional information reduces the chance that investments will be made in projects that turn out to be unprofitable *ex post*, the net present value of a postponed investment can be higher than the net present value of an earlier investment. In other words, the combination of uncertainty with irreversibility will result in situations in which investments are negatively related to the degree of uncertainty.

In conclusion, both the evolutionary and the “new” neo-classical literature address the issue of uncertainty, and convergence has taken place in modeling innovation as a stochastic process. Still, the role of uncertainty has mainly been elaborated in “evolutionary Schumpeterian” growth models. Again, it has to be noted that the latter comes at a certain price. Making stochastic processes the crucial mechanisms that drive innovation and diffusion may prevent the models from illuminating the actual mechanisms determining an aggregate pattern of technological change (see, e.g., [63]).

4.4. Irreversibility and path dependency

The issues of “path dependency” and “lock-in” are characteristics of technological innovation and diffusion processes and thus important “products” of evolutionary economic theorizing. Path dependency refers to the role of historical events in determining the adoption of technologies (see [65]). This implies a certain degree of irreversibility and, hence, the possibility of technologies to get locked-in to a technological paradigm [66].

In growth theories, these topics have been addressed in basically two ways. First, irreversibility in the “evolutionary Schumpeterian” growth models is generally implicit to the notion of “creative destruction,” as it is in “neo-classical Schumpeterian” growth models in the notion of the business stealing effect. That is, innovation and diffusion of technologies displace older technologies imposing irreversible losses to the agents that are locked-in to outdated technologies (see, e.g., [7,46]). In line with this, the existence of vested interests among agents specialized in the old technologies may cause resistance to the adoption of new technologies and, hence, slow down technological progress (see [67–69] for many historical examples, and [70] for a theoretical approach to this issue). It is also here that “evolutionary Schumpeterian” and “neo-classical Schumpeterian” models come close together, because they both stress the role of increasing returns to adoption, returns on learning by doing, network externalities, and technological spill-overs in establishing vested interests and lock-in situations. Second, irreversibility and path

dependencies play a role in growth theory in terms of permanent effects of temporary shocks on macrodynamics.

5. Conclusions

Over the last two decades, a renewed interest in economic growth theory has emerged. Dissatisfaction with the “old” neo-classical theories of economic growth, rooted in the pioneering contributions of Solow and Swan [1,2] resulted in two new classes of models of economic growth and technological change: neo-classical endogenous growth models, and evolutionary growth models. The first class of models has been labeled endogenous after their key feature to make technological change endogenous. Following the work of Nelson and Winter [6], the second class of models endogenizes technological change as well, but according to an evolutionary view on economic growth and technological change, emphasizing the importance of heterogeneity, uncertainty, and path dependency.

The two approaches converge in what is called a Schumpeterian view on economic growth and technological change. The essential characteristic of this approach is the occurrence of a succession of innovations in one or more sectors, resulting from research activities, and implying a business stealing effect. Differences between the “evolutionary Schumpeterian” and the “neo-classical Schumpeterian” growth models can mainly be traced back to the way they deal with heterogeneity, uncertainty, and path dependency. It can be argued that in evolutionary models, technological and behavioral diversity, uncertainty, path dependency, and irreversibility are elaborated in a more sophisticated and explicit way than in neo-classical growth models. However, it has to be noted that this level of microeconomic diversity comes at a certain price. Due to the complexity of the models, which precludes analytical tractability, the mechanisms behind the aggregate dynamics are not always clearly exposed. In other words, although the evolutionary tradition in economics claims to enter further into the technological “black box” [71], it does not always avoid the pitfall of substituting Solow’s “manna from heaven” for “parameters from heaven.”

Nelson and Winter have formulated the challenge to an evolutionary formulation as follows: “it must provide an analysis that at least comes close to matching the power of neo-classical theory to predict and illuminate the macro-economic patterns of growth. And it must provide a significantly stronger vehicle for analysis of the processes involved in technical change, and in particular enable a fruitful integration of understanding of what goes on at the micro level with what goes on at a more aggregated level” ([6], p. 206). It can be argued that although evolutionary modeling has evolved since the Nelson and Winter model, evolutionary growth theory has demonstrated relatively little progress in terms of formal theorizing. So far, evolutionary growth models did not yield much new insight in or a better understanding of the mechanisms driving macroeconomic patterns of economic growth and technological change. A challenging task for further research is to combine the fruitful insights of both the neo-classical and the evolutionary perspective to improve our understanding of the complex processes of technological change in relation to other macro- and microeconomic processes.

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